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Requirements Driven Design of an Imaging Spectrometer System for Characterization of the Coastal Environment

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ABSTRACT

A wide variety of applications of imaging spectrometry have been demonstrated using data from aircraft systems. Based on this experience we have developed requirements for a satellite imaging spectrometer system to best characterize the littoral environment, for scientific and environmental studies and to meet Naval needs. This paper describes the process for determining those requirements and the resulting Hyperspectral Remote Sensing Technology (HRST) program. The HRST spacecraft has a Coastal Ocean Imaging Spectrometer (COIS) with adequate spectral and spatial resolution and high signal to noise to provide long term monitoring and real-time characterization of the coastal environment. It includes on-board processing for rapid data analysis and data compression, a large volume recorder, and high speed downlink to handle the required large volumes of data. This is a joint program with an industrial partner, and their commercial remote sensing requirements are included in the system design.

Keywords: coastal, imaging spectrometry, oceanography, optical remote sensing, hyperspectral sensing

1. INTRODUCTION

The Navy is in the midst of a fundamental shift away from open ocean warfare on the sea towards joint operations from the sea. To support that effort the Navy and Marine Corps need methods for determining shallow water bathymetry, topography, bottom type composition, detection of underwater hazards, water clarity and visibility[1]. Visible radiation is the only electromagnetic tool that directly probes the water column, and so is key to naval systems for bathymetry, mine hunting, submarine detection, and submerged hazard detection. Unfortunately, none of the present or, until now, planned remote sensing instruments are ideal for assessing the health of the coastal environment. Ocean color instruments have 1 kilometer resolution which is not adequate for the more complex coastal regions, and they suffer from ringing and other problems near the shore. Instruments such as Landsat, SPOT and the planned higher resolution instruments do not have the correct bands to penetrate the water, and do not have adequate signal to noise. The ideal coastal ocean instrument would have high spectral resolution and high signal to noise for maximum water penetration and moderate spatial resolution for resolving the complexities of the coastal ocean. To meet these requirements we have designed a Coastal Ocean Imaging Spectrometer (COIS). This paper discusses the Hyperspectral Remote Sensing Technology (HRST) program to characterize the coastal ocean using COIS, the instrument design requirements, and an automated processing system to handle the large volumes of data.

2. DEVELOPMENT OF THE HRST PROGRAM

In the open ocean optical properties are primarily determined by the growth of phytoplankton and associated detrital products. Analysis of data from NASA's Coastal Zone Color Scanner (CZCS, 1978-1986)[2] demonstrated the usefulness of multispectral imagers for the estimation of phytoplankton chlorophyll and water clarity for the open ocean at 1 to 20 km spatial resolution. This success has lead to the development of the Sea-viewing Wide Field-of-view Sensor (SeaWiFS, to be launched in late 1997)[3] and similar Japanese and European instruments. However, ringing from bright targets such as land and clouds, limited spatial resolution, and the use of only 3 or 5 bands for measurement of the in-water optical properties limits their usefulness in the coastal waters. For example, planned SeaWiFS data processing excludes processing data from water with depths less than 60 feet because of bottom reflections or less than 5 pixels (5 km or 3 miles) from the coast because of stray light and ringing problems.

To address the problems of the coastal ocean we have been working since 1990 using the Airborne Visible/InfraRed Imaging Spectrometer (AVIRIS)[4,5] which is operated by the Jet Propulsion Laboratory and flown on an ER-2 operated by NASA Ames. AVIRIS data provides 20 m spatial resolution and 220 spectral bands covering .4 to 2.4 micron spectral range at 10 nm resolution. In a series of experiments we have demonstrated the ability to use AVIRIS data to separate the chlorophyll signal from bottom reflectance in clear waters of Lake Tahoe[6] and the turbid waters offshore from Tampa Bay[7]. In addition, spectral signals from re-suspended sediments and dissolved organics have been interpreted for the Tampa AVIRIS images[7,8], and for suspended sediments and kelp beds for AVIRIS images of San Pedro Channel[9]. These results lead to a general semi-analytical model for decomposition of the spectral signatures[10,11].

The HRST program was developed to demonstrate the use of imaging spectrometry to meet Naval requirements for the characterization of the coastal ocean. The HRST program includes flying the COIS instrument on a small earth observing satellite together with a commercial 5 m panchromatic imager and an Imagery On-Board Processor (IOBP) which will use the Optical Real-time Adaptive Spectral Identification System (ORASIS) for onboard processing and data compression. ORASIS on-board processing identifies the underlying spectral signatures in a scene and coincidentally results in a > 10x data compression of the data. This makes possible the collection of a larger data set, and the demonstration of the tactical downlink useful products to Naval forces. The program also includes the characterization of 40 - 50 coastal regions using COIS data products and the development of dynamical models of the coastal environment which are validated using those products.

To make the most effective use of limited funding HRST is being pursued as a government - industry partnership. This is an advantage to the government because industry shares the cost of the construction, launch and operation of the satellite. The advantage to the industrial partner is the opportunity to collect COIS data and coincident 5 m panchromatic data to produce their commercial data products, and to make use of the government algorithms and ORASIS processing software to cost effectively produce useful products from the COIS data. For example, the 5 m panchromatic data can be used to sharply define the extent of a farmers field, and the hyperspectral data to identify the crop in the field, and to assess the health of the crop and identify the need for more or less, water, fertilizer or pest control based on variations in the spectral properties across the field. The industrial partners will also exploit the value of imaging spectrometry data for environment assessments and mineral exploration.

3. COIS DESIGN REQUIREMENTS

Design requirements for COIS are based on extensive experience using AVIRIS for coastal ocean measurements, and on the studies done for the development of SeaWiFS (Table 1). The orbit was selected by balancing the need to be low to make the telescope smaller, and to be higher to minimize drag and save fuel. Something in the 500 to 650 km range is ideal. Within that range the 605.5 km orbit was chosen to provide a 7 day ground track repeat cycle that is optimal for this mission. A near noon equatorial crossing time is required to have the maximum amount of sunlight penetrating the ocean. Ten thirty a.m. is selected to minimize the small cumulus clouds build up over the tropical ocean in the afternoon.

Features in the coastal ocean , such as fronts, bars or reefs, are on the scale of a few hundred meters so 60 m sampling is adequate for the coastal ocean. However, some bottom features, and the adjacent land features are typically on a smaller scale and 30 m (Landsat Thematic Mapper resolution) or better sampling is preferred. both modes are supported by the COIS instrument. The commercial partners will use the 30 m mode for specific requested sites, and the 60 m mode for large area mineral mapping and crop evaluation.

A 30 km swath width is considered minimal to sample the coastal ocean and some of the adjacent land areas. Given that requirement higher resolution means higher data rate and a larger more expensive focal plane. The COIS instrument has 1024 x 1024 focal planes on the VNIR and SWIR cameras. Pixels are summed by 16 and 8 respectively in the VNIR and SWIR to achieve the desired spectral resolution. A co-registered, 5 m resolution panchromatic band imager is required to help locate coastal and land features and for more precise mapping of the images.

For rapid response to events, and for more frequent revisits for temporal studies across-track point is used to reduce the revisit time. Across track pointing of ±30° gives an average 2.5 day re-access time to any location on earth, without causing the problems with atmospheric correction or low signal that would result from using more extreme viewing angles. Pointing is achieved by slewing the spacecraft. Along-track pointing is required to avoid sun glint. Experience with the CZCS has shown that ±20° is adequate for most conditions. Pointing ± 30° along track is also used to increase integration time when sampling in the 30 m mode. this technique is called Image Motion Compensation (IMC). At the beginning of a scene the spacecraft is pointed forward then the spacecraft slews slowly aft so that the instrument is staring at the ground for an increased period of time for each pixel. In the 30 m mode a 4.5 times increase in integration time is needed to meet the required signal-to-noise ratio for ocean measurements.

Table 1. Functional requirements for the Coastal Ocean Imaging Spectrometer.

Functional Requirement	**Value**	**Comments**
Orbit	500 - 650 km, sun synchronous, 10:30 - 1:30 equatorial crossing time	Trade-off of instrument performance vs. orbit stability
Ground Sample Distance (GSD)	30 to 60 m	Trade-off of resolution vs. swath width and integration time
Panchromatic GSD	5 m	Panchromatic band for accurate location of coastal features and commercial applications
Swath width	30 km	Requires 512 to 1024 across-track pixels
Pointing	±30° across track, ±30° along track	Across track for 2.5 day revisit, along track to avoid sun glint and for image motion compensation
Spectral range	400 - 2500 nm	Two spectrometers; VNIR only adequate for ocean, but SWIR needed for adjacent land areas
Spectral sampling	10 nm	Resolution needed to resolve natural spectral features
Signal-to-noise ratio for 5% reflectance, 400-1000 nm	200	The ocean is a dark target and 90% of the signal that reaches the instrument is from the atmosphere
Signal-to-noise ratio at 5% reflectance, 1000-2500 nm	100	Land targets have a higher reflectance
Polarization sensitivity	<5%, goal <2%	To avoid complications from polarized skylight reflecting off the sea surface
Radiometric calibration	3-5% (best current practices)	Necessary for change studies

The minimal spectral range for the ocean measurements is 400 to 1000 nm which could be covered with a single CCD spectrometer instrument. However the SWIR data is extremely valuable for the land areas and is included primarily in support of the commercial imaging requirements. The spectral sampling is 10 nm. Considerable experience with field spectrometers, and AVIRIS data has shown that this is the minimal sampling required to resolve most natural ocean and land spectral absorption features which are on the order of 20 to 40 nm in width.

The SNR requirement is that the minimum SNR over the 400 - 1000 nm range should be greater than 200 for a 5% reflectance scene. This is a very stringent SNR requirement because the sensitivity of most instruments falls off rapidly below 500 nm. Typically, an instrument SNR is quoted at its peak sensitivity in the visible (usually around 650 nm) and for a land reflectance of 30 -50%. A typical instrument designed for land remote sensing would have a SNR of 400 - 500 on that scale, but would have a SNR of only 10 to 20 at 400 nm for a 5% reflectance scene. The reason the requirement is stated in this way is that much of the important spectral information in an ocean scene is in the 400 - 500 nm range. Further, the ocean is a very dark target, <5% reflectance except when there are large amounts of suspended sediments or a strong signal off the bottom. Thus, on the order of 90% of the signal that reaches the instrument is from the atmosphere, so the SNR must be very high if there is to be good resolution of the ocean signal. The requirement is less stringent for the longer wavelengths which do not penetrate the ocean because the land reflectances are higher, typically in the 20 to 50% range.

The sky is highly polarized, and the polarization is dependent on the sun elevation and azimuthal angle, the viewing geometry, wind speed and the amount of aerosols. Although ocean measurements are made at angles to avoid direct sunglint, some skylight is always reflected off the sea surface into the sensor. If the sensor is insensitive to the polarization of the light simple models can be used to correct for the reflected skylight. However, if the instrument is sensitive to polarization then the correction is much more complex and requires good auxiliary measurements of wind speed and aerosols. The best way to avoid this potentially large source of error, is to make the instrument as insensitive to polarization as possible.

Good calibration is required for these measurements in order to extract quantitative estimates of phytoplankton, suspended sediments or other materials in the water. Also, good calibration is required to do change detection, using a series of measurements over time. Errors in calibration could obscure real changes in the environment. Conversely, changes in calibration could be misconstrued as a real change when there is none. Good calibration includes careful laboratory calibration before flight and during thermal-vacuum testing, and then some method of regularly checking the instrument performance during flight. COIS calibration will be maintained on orbit by viewing moon and large uniform ground reference targets including the Sargasso Sea and the Bonneville Salt flats, with known and monitored reflectances.

The performance requirements are challenging, however, several designs have been proposed that will meet all of these requirements. The basic COIS design is a dual spectrometer system with a silicon CCD detector for the visible and Mercury-Cadmium-Telluride detector for the short wave infrared (SWIR). The SWIR array is cooled with a pulse tube cooler to 110°K. The design uses an off-axis telescope, a dichroic beam splitter and separate VNIR and SWIR spectrometers. It is anticipated that the instrument will be provided by a commercial instrument builder that will become a partner in the program.

4. DATA PROCESSING AND ANALYSIS

To deal with the flood of data produced by imaging spectrometers the Plasma Physics and Remote Sensing Divisions of the Naval Research Laboratory have had a joint program for the last four years to develop an automated system for the processing and rapid analysis of hyperspectral data. This effort led by Peter Palmadesso and John Antoniades has resulted in the development of The Optical Real-time Adaptive Spectral Identification System (ORASIS). The approach is to analyze each spectra in the scene sequentially, discarding duplicate spectra, and working only with the unique spectra and the map of their location in the scene. Using convex set methods and orthogonal projection techniques each observed spectrum is then analyzed in terms of the set of vectors that represent the physically meaningful basis patterns that have combined to make the observed spectrum. Then matched filters (Filter Vectors) are created and used to demix the image[12,13]. Successive improvements in the software have lead to a highly accurate and very rapid processing system that has been implemented on DSP processors for real time processing of aircraft imaging spectrometer data. An Imagery On-Board Processor (IOBP) has been designed to run ORASIS in real time on the HRST satellite. A breadboard IOBP is being constructed and the DSP boards are undergoing space qualification testing.

On-board processing has two advantages, it allows rapid analysis of the data, and it eases the data downlink problem. ORASIS processing results in 10 to 20 endmembers for a typical scene. The endmembers are small files, and the matched filter vectors are the same size as a single band image. Thus ORASIS processing resulting in 10 to 20 endmembers means a factor of 10 to 20 reduction in data volume compared with the original 200 spectral bands. The result is the ability to take, process and downlink far greater amounts of data. If there is a requirement to work with the raw spectral data the dot product of the spectral endmembers and their filter vectors can be used to reconstruct the original data cube with essentially no loss of data.

5. CONCLUSIONS

COIS is a compact high performance imaging spectrometer which will meet the high signal to noise requirements for the coastal ocean and provide excellent land data for commercial crop and environmental assessments and mineral exploration. COIS is matched with an on-board ORASIS processor for near real-time processing of the data. ORASIS processing results in 10 to 20 endmembers for a typical scene which means a factor of 10 to 20 reduction in data volume compared with the original 200 spectral bands. The result is the ability to take, process and downlink far greater amounts of data. For example, COIS will provide more data each day of operation than the total data downlinked during the lifetime of the Hyperspectral Imager planned for the NASA Lewis mission. The COIS-ORASIS combination overcomes the cost and data volume problems associated with imaging spectrometry and will help make hyperspectral imaging a practical reality.

HRST is a requirements driven, cost constrained program. A space mission must be built on clearly defined requirements if it is to achieve scientific, commercial, or government goals. In today's funding environment minimizing costs is essential, but this should never be at the sacrifice of the primary mission goals. A purely cost constrained mission that sacrifices its primary goals to stay on budget ends up being unproductive, and thus not a cost effective program.

Without making sacrifices that negate the primary mission goals there are several ways to improve efficiency and reduce costs. First, aggressively seek partners who can benefit from sharing the instrument or spacecraft without jeopardizing the primary mission. In the case of HRST the commercial partners data requirements are easily met by the spacecraft operations. Without jeopardizing the Naval mission they bring cost sharing, a commercial spacecraft that is being modified for the program, and considerable expertise in many aspects of the program. Second, whenever possible take advantage of commercial or government off-the-shelf components that can make the program less expensive. Unless it is a primary goal of the program to advance a particular technology use of the latest off-the-shelf technology is the cost effective choice. Third, as early as possible, study design trades and simulate on-orbit performance and day in the life scenarios. These tools are essential to evaluate the effects of adding a partner who needs additional data from certain areas, and make trades on components that have complex interactions with each other. For remote sensing satellites instrument performance, on-board data processing and storage, data downlink, and ground processing all interact in complex ways. It takes realistic simulations and trade studies to select the best, most cost effective combination of these expensive components. there are many other ways of controlling costs, but these three approaches have been particularly effective in the development of the HRST program.

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